

Unmanned ground vehicle perception using thermal infrared cameras

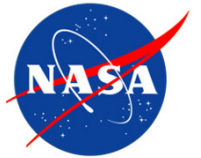
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*This research was carried out by the Jet Propulsion Laboratory,
California Institute of Technology, under the Robotics Collaborative
Technology Alliances program, through an agreement with NASA.*



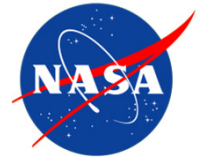
Topics Addressed







- TIR cameras used by JPL/GDRS for UGV programs
- Calibrating TIR stereo cameras
- Dense stereo ranging with TIR cameras
- Terrain classification
 - Soil vs. vegetation
- Obstacle detection
 - pedestrians, vehicles, negative obstacles, water bodies
- Perception thru obscurants
- Summary



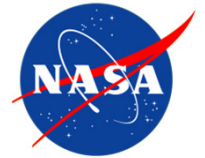
Specs of Sample TIR Cameras



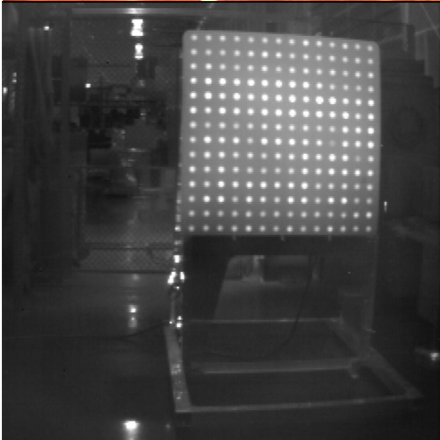
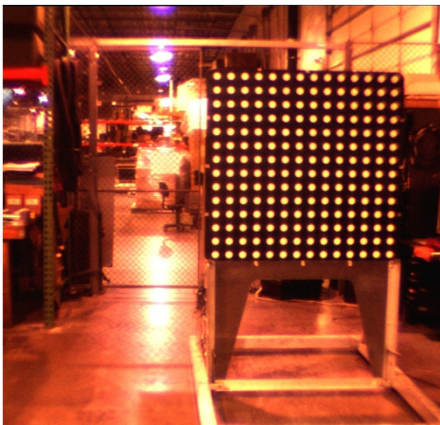
Program Year	Demo III 2001	PerceptOR 2002	PerceptOR 2002	RCTA 2011
Camera	Cooled Merlin MWIR 	Cooled NC256 MWIR 	Uncooled Alpha LWIR 	Uncooled Photon LWIR 
Power (W)	30	16	1.5	<3
Size (cm)	14x12.7x24.9	7.1x7.1x29.5	4.3x4.3x10.9	6.2x6.4x4.6
Mass (g)	4082	1350	140	170
Sensitivity (mK)	<25	<20	unknown	<50
Exposure time (ms)	0.005	0.1	33	13-14
Resolution	320x256	256x256	160x128	644x512



Calibrating TIR Stereo Cameras



2000, JPL-Demo3
Lab fixture with
plastic inserts heated
by light bulbs



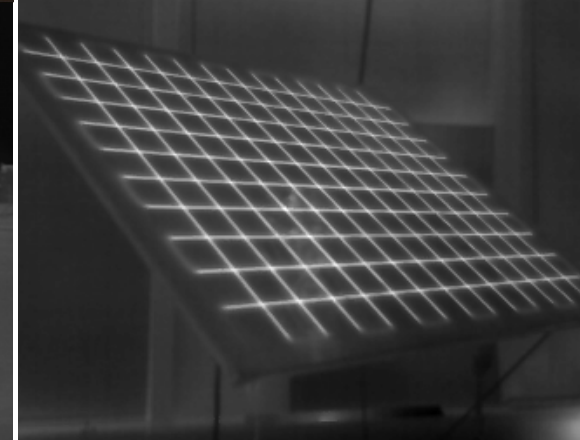
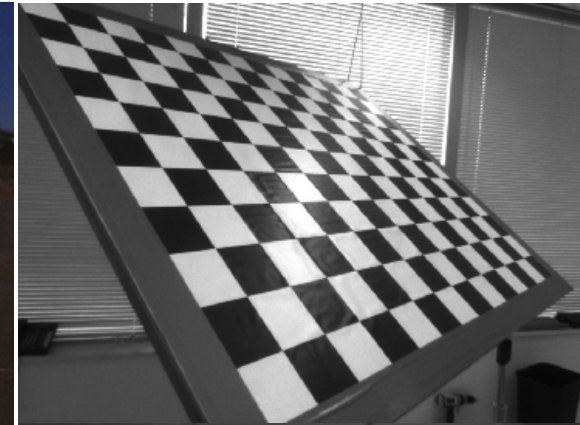
Heating not uniform

2002, JPL-PerceptOR
Dot pattern on portable
foam core board heated
by the sun



Not usable on
overcast day

2010, GDRS-RCTA
Grid of fine wires aligned
with transition lines heated
by current flow

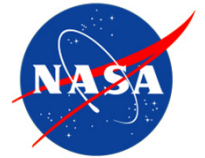


Color
image

Thermal
infrared
image

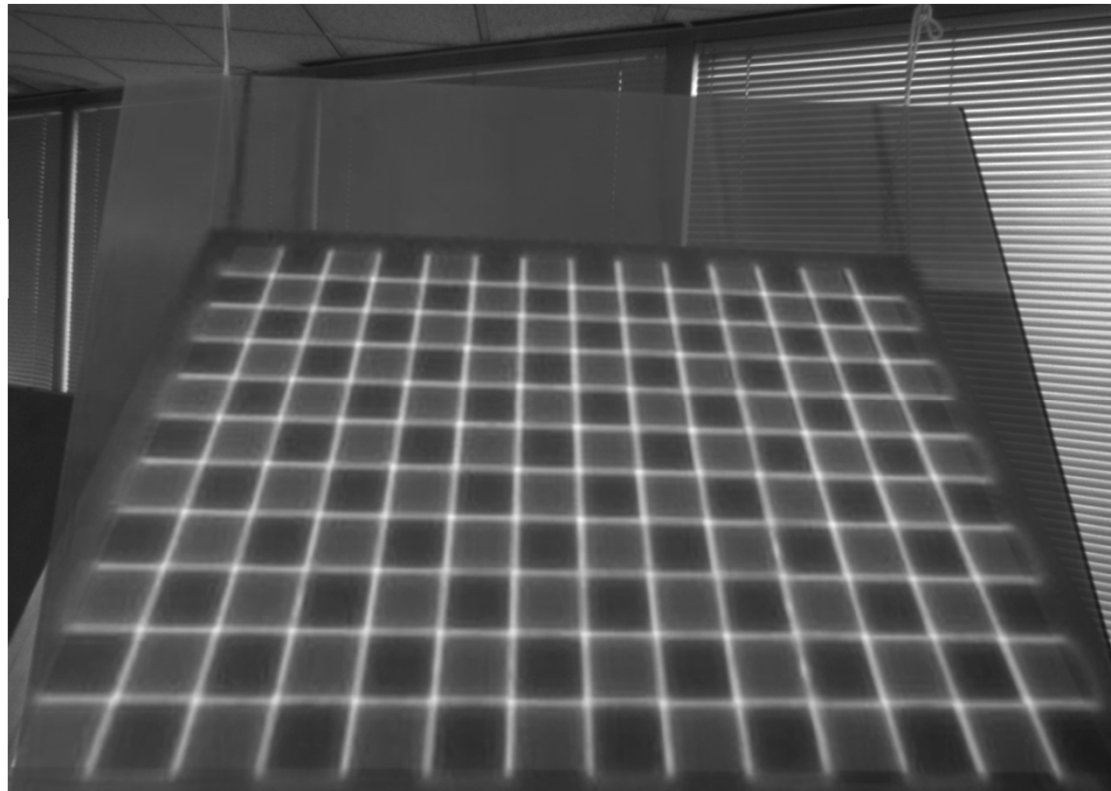


GDRS Multispectral / Multimodal Calibration Target



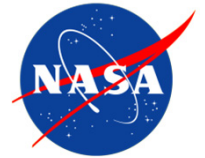
- Pattern aligned, laminated SWIR / LWIR-lighting wires provide commonly located square corners
- Reverse-side printed pattern presents consistent matte material (lexan®) surface
- Rigid aluminum honeycomb support panel presents metallic surface for RADAR & SONAR

LWIR View
Overlaid on
Visible View

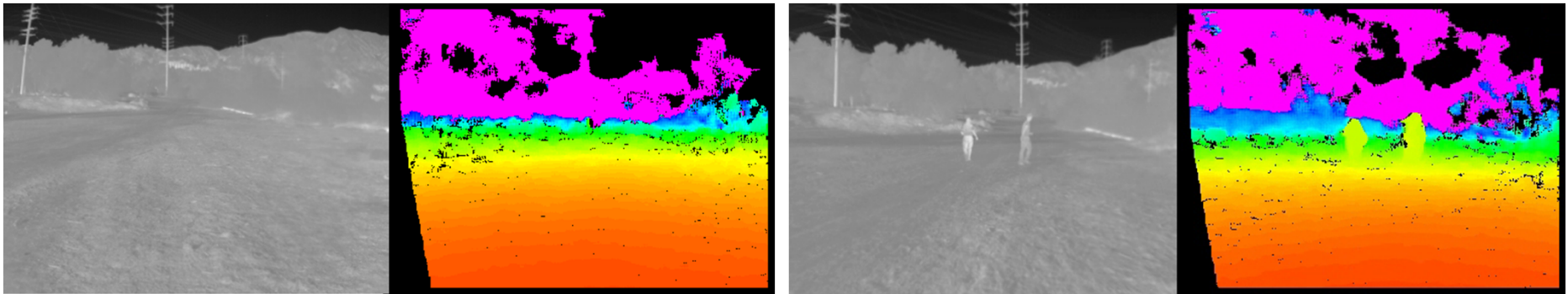




Dense Stereo Ranging



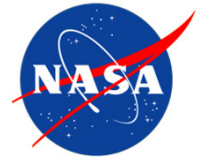
- Real-time stereo algorithms work with color and TIR cameras
- Issues that affect the quality of TIR dense stereo range data
 - Image blur
 - Scenes with low texture
 - Poor calibration



Example stereo range images from stationary UGV, 3pm
Thermoteknix Miricle 110KS LWIR cameras
384x288 pixels, 31cm baseline, 7ms time constant

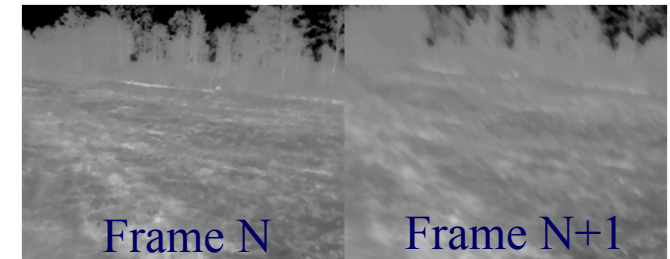


Image Blur



- Image blur occurs when there is too much motion during the exposure time
- Since uncooled LWIR cameras have long exposure times, they are susceptible to image blur

Image blur due to high UGV pitch rate on rough terrain



General camera motion

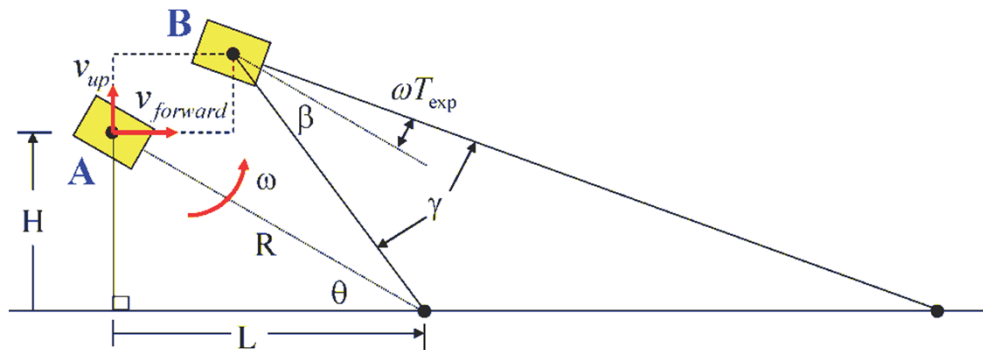
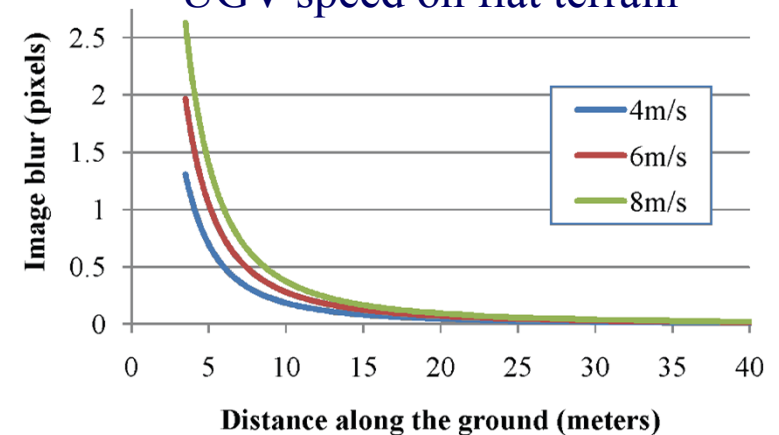


Image blur equation

$$P = \frac{\tan^{-1} \left[\frac{v_{forward} T_{exp} \sin \theta + v_{up} T_{exp} \cos \theta}{R - (v_{forward} T_{exp} \cos \theta - v_{up} T_{exp} \sin \theta)} \right] + \omega T_{exp}}{IVFOV}$$

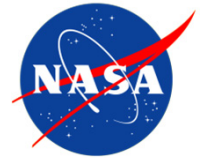
Image blur as a function of UGV speed on flat terrain



(Assumptions: IVFOV=2.24mrad, H=1.53m, 5° down tilt)



Image Blur Effect on Stereo



- A UGV was manually driven over a dirt trail at several different speeds at ~3pm on a sunny day
- Minor loss in stereo range data with increasing speed

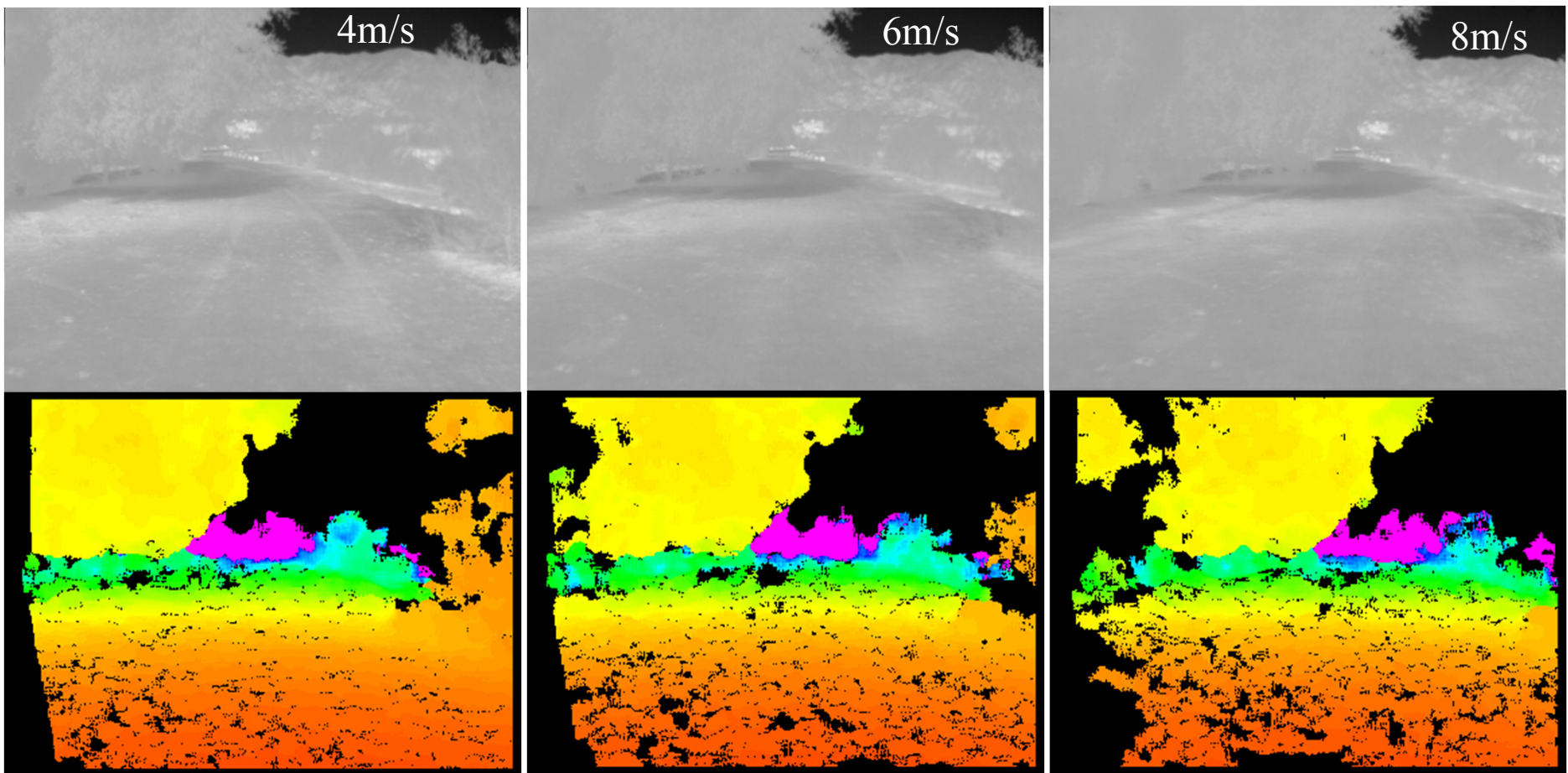
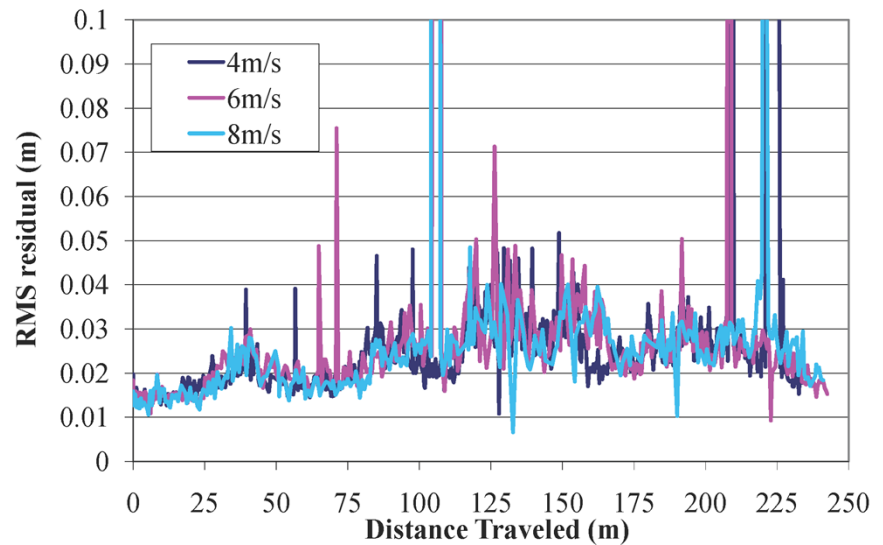
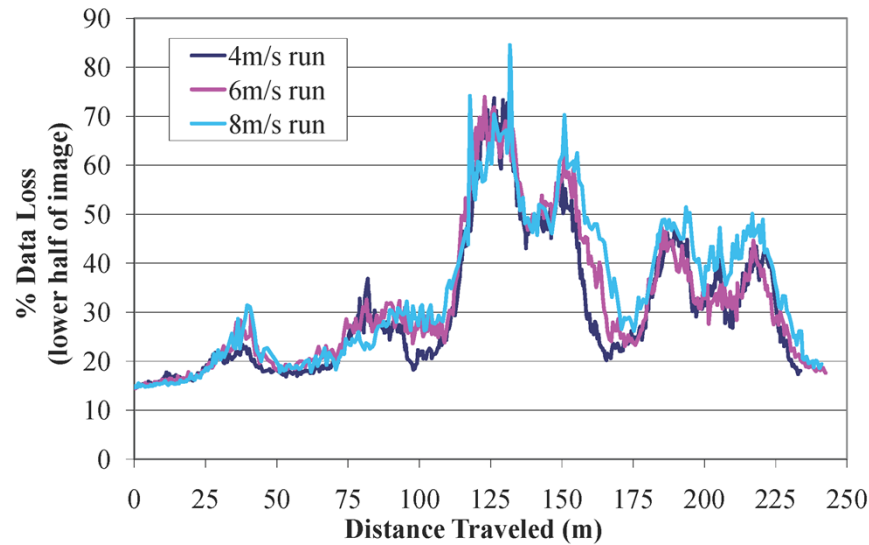
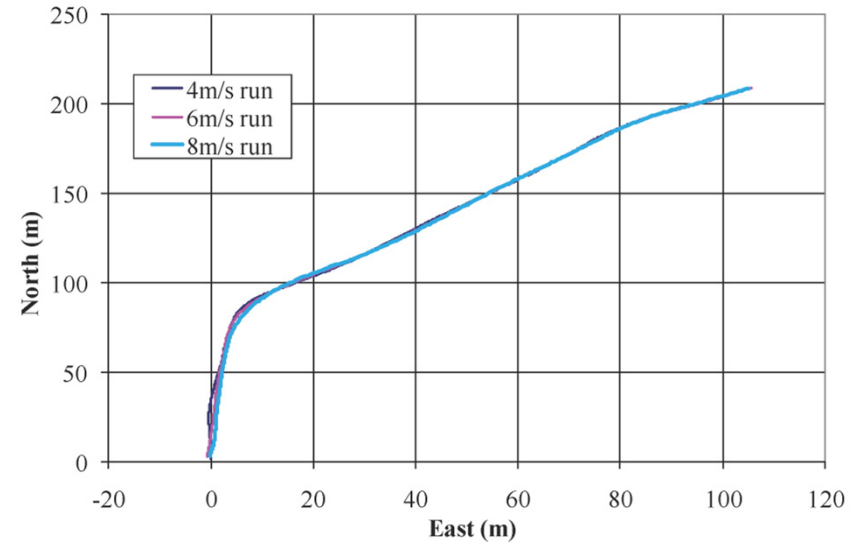
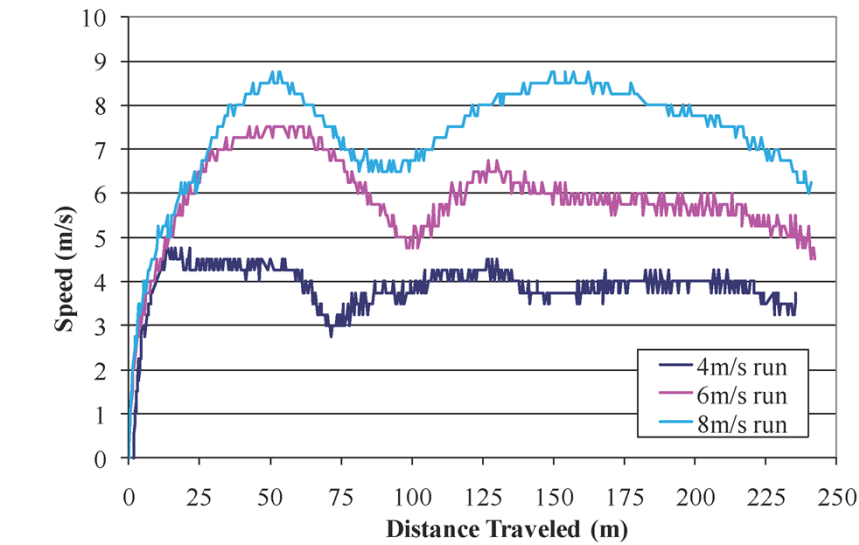
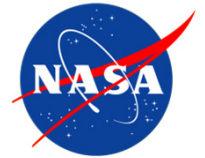


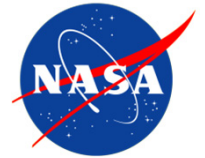


Image Blur Effect on Stereo

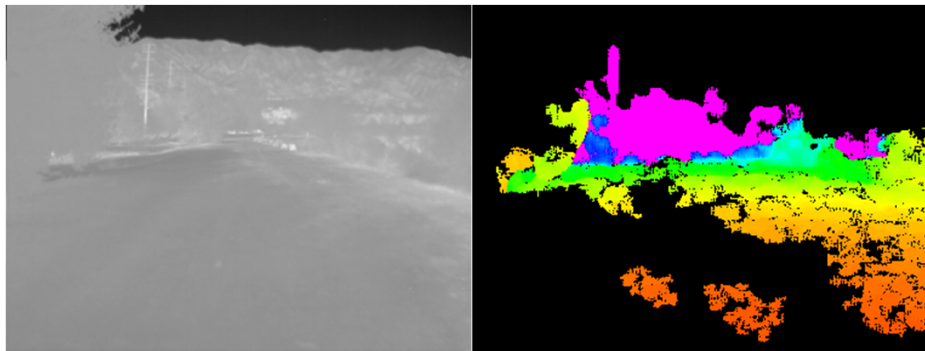




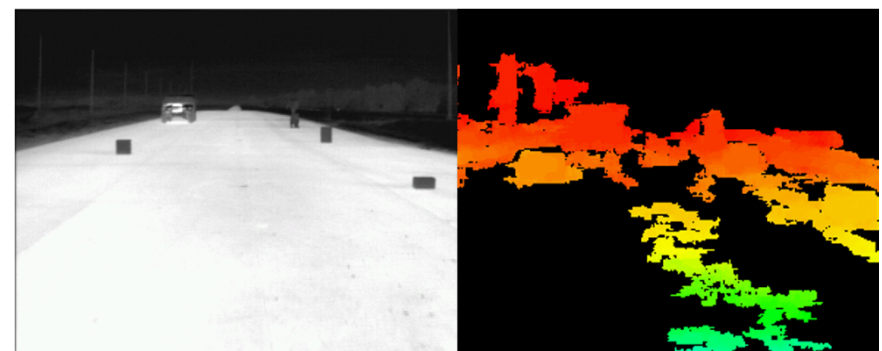
Low Texture Effect on Stereo



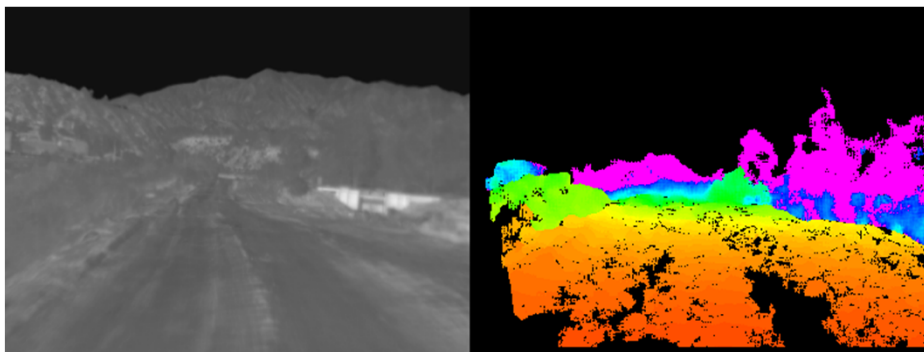
- Poor stereo correlation due to low texture can occur with cooled and uncooled TIR cameras
- Performing AGC on a region of interest that excludes the sky can improve stereo data density



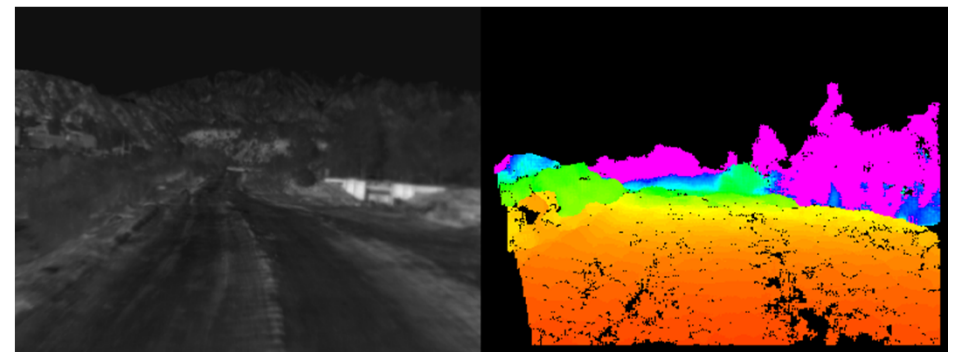
Miricle 110KS Uncooled LWIR:
Portion of dirt trail with low texture



Merlin Cooled MWIR:
Blacktop surface heated by the sun



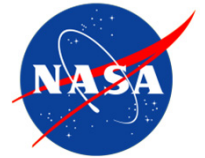
AGC performed over the entire image
(from 12 m/s sequence)



AGC performed over the lower $\frac{3}{4}$ of the image
(from 12 m/s sequence)

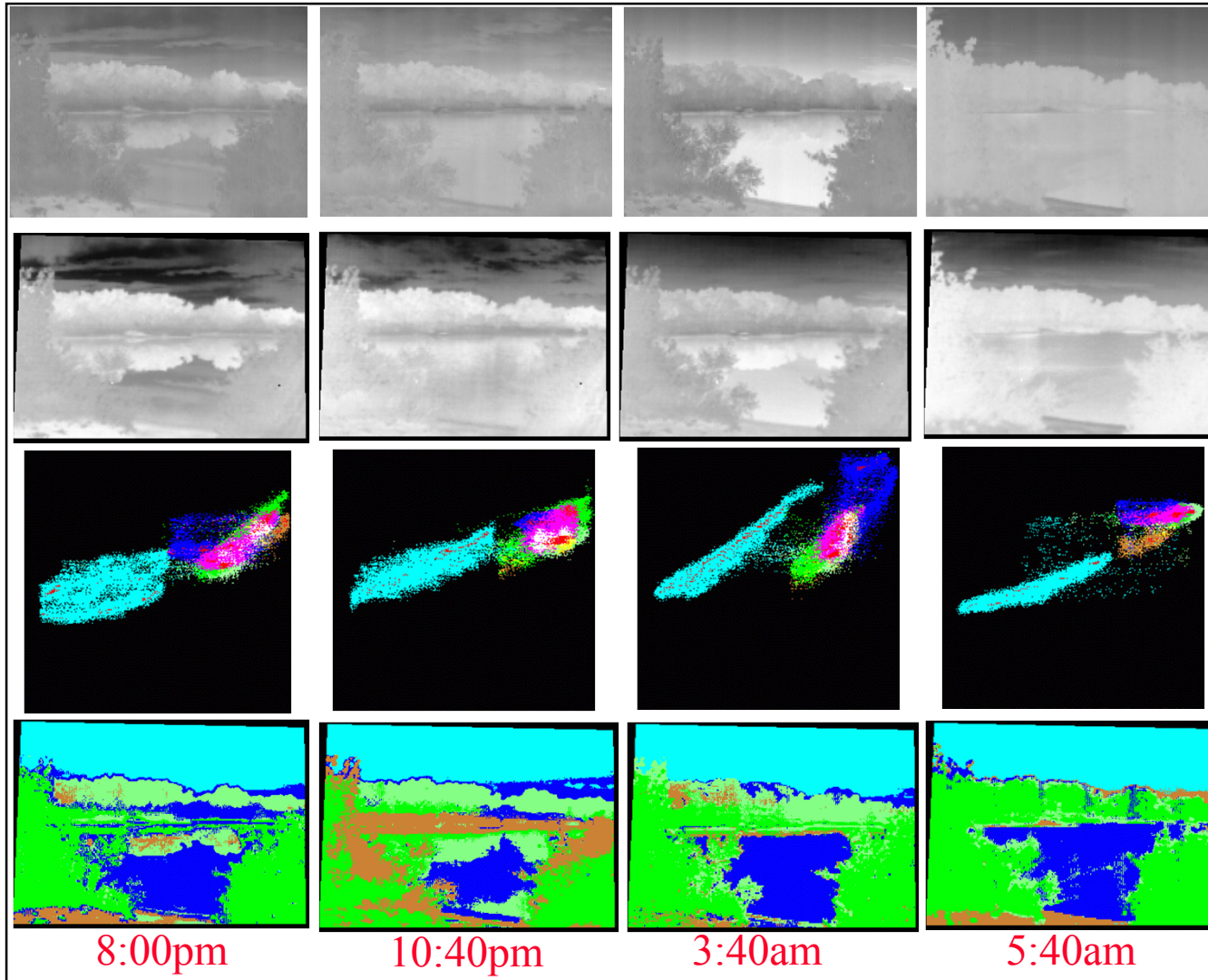


Dual Band Terrain Classification



Scene from
Chatfield State
Park, CO

Mahalanobis
distance
classifier, 4
nighttime
periods
independently
trained.



MWIR
images

Cropped/
warped
LWIR
images

2D
histogram
(MWIR
vs.
LWIR)

6 class
result

8:00pm

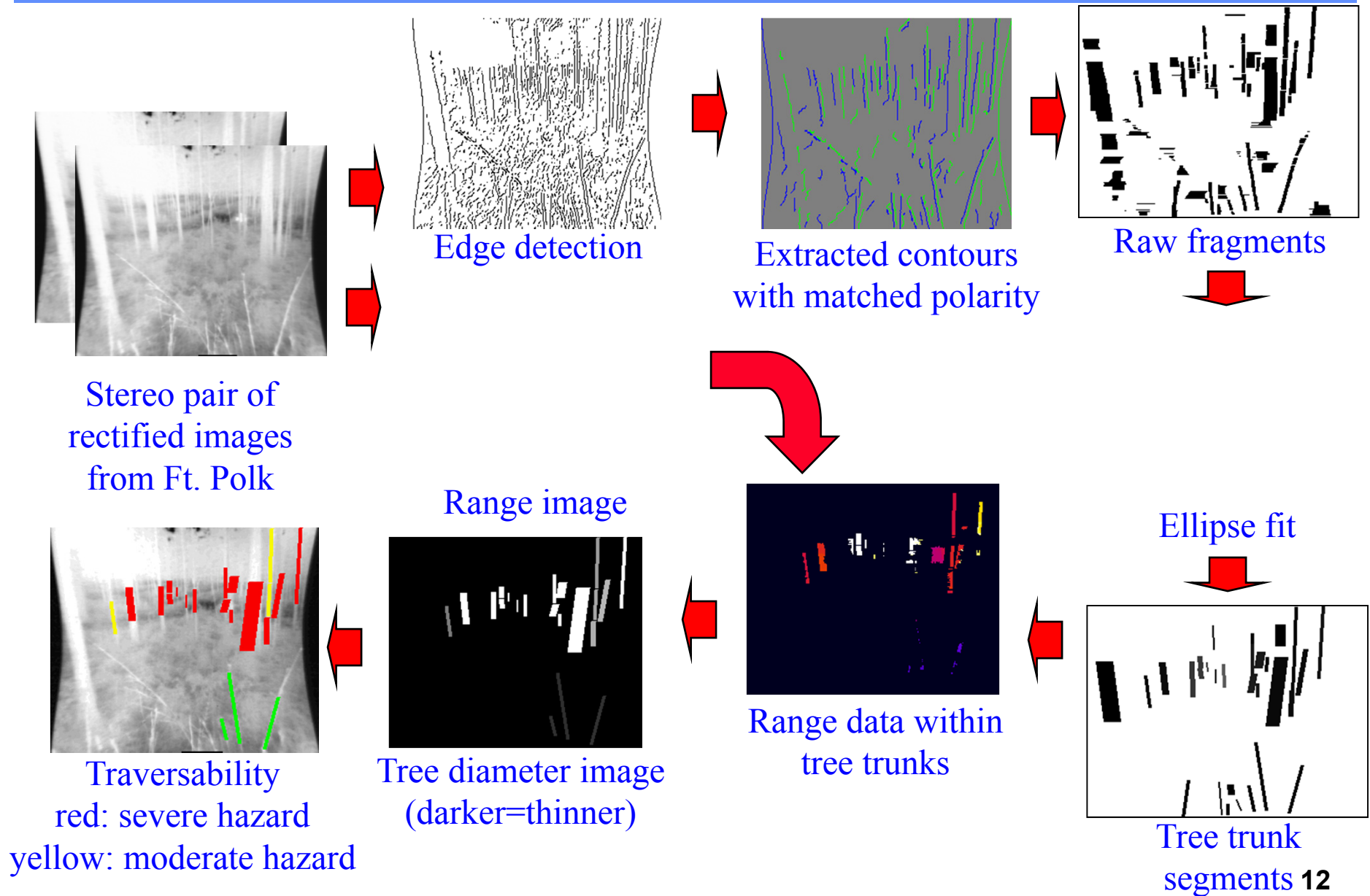
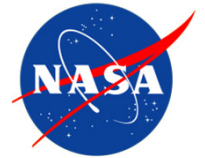
10:40pm

3:40am

5:40am

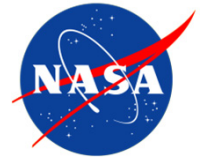


Tree Trunk Detector

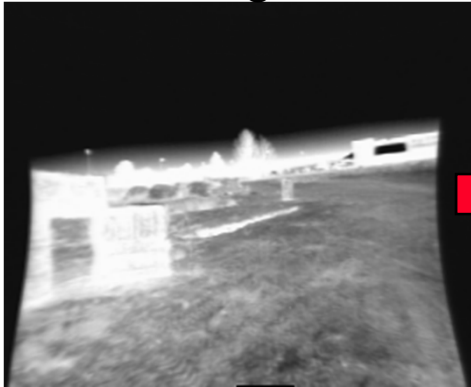




Negative Obstacle Detection



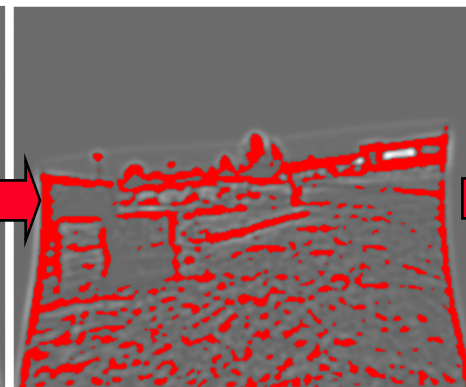
Rectified intensity
image



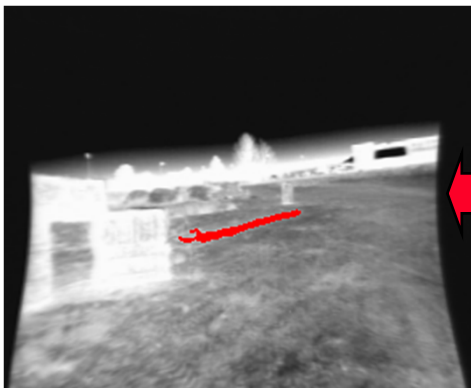
LoG image ($\sigma=1.75$)



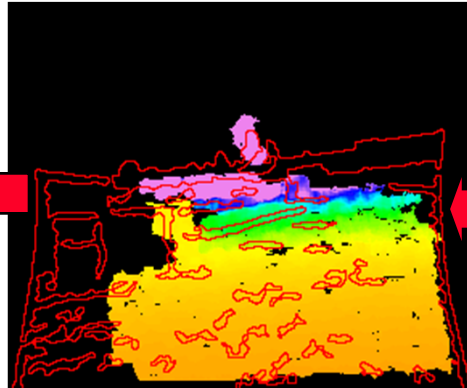
Pixels w/ negative
values < -1.8



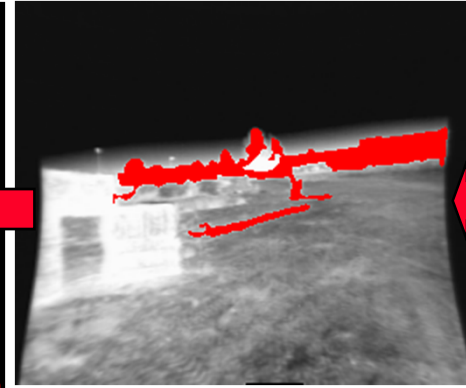
Closed contours after
small blob removal



Final result



Perform geometry
based filtering



Candidate negative
obstacles

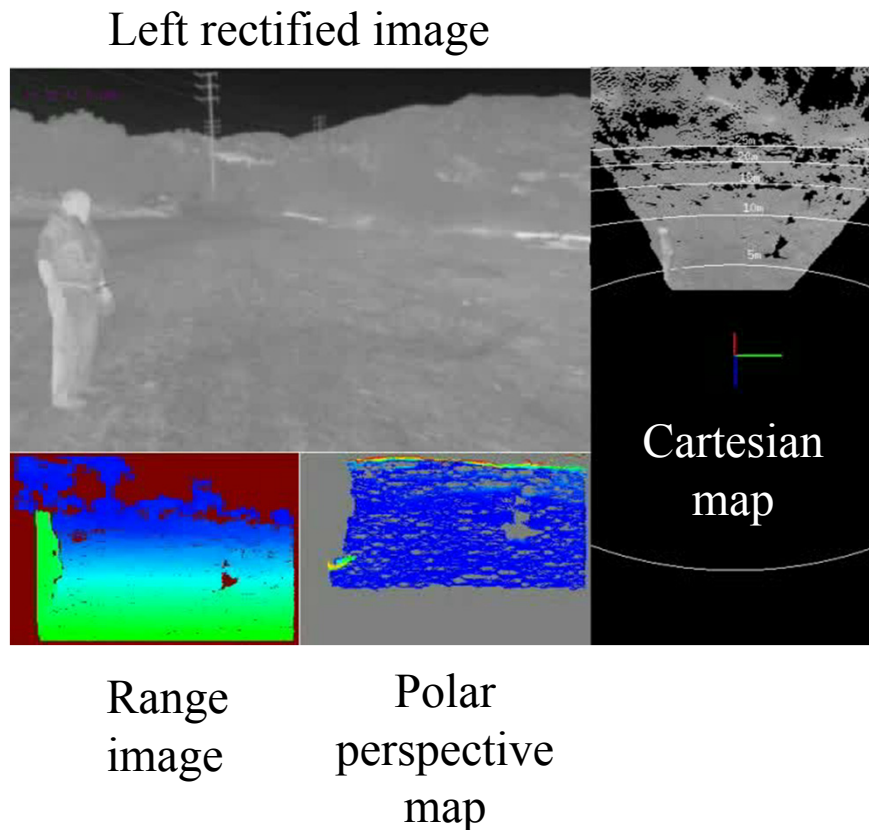
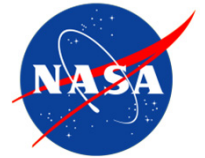


Normalized intensity
difference image

Ditch warmer than surround @ night. First detection at 18m (3 pixels wide) 13



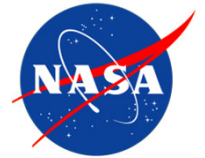
Pedestrian Detection



- Approach
 - Generate dense stereo range data
 - Perform visual odometry to compute the change in pose of the UGV
 - Detect and segment regions of interest in the 3D stereo point cloud which have a width and height consistent with an upright human
 - Classify each region of interest with a probability of being human
 - Track the regions of interest over multiple frames.



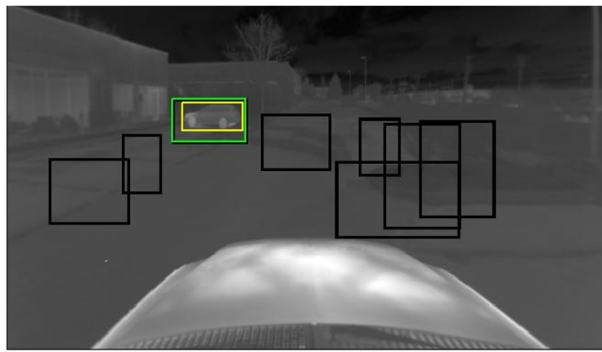
Vehicle Detection



- Initially implemented to improve the detectability of partially occluded pedestrians, and reduce pedestrian false alarms
- Stage 1:** large blobs in stereo range point cloud are extracted and assigned a feature vector
- Stage 2:** feature vector of each extracted blob is passed to a linear classifier which determines whether or not the blob is a vehicle.

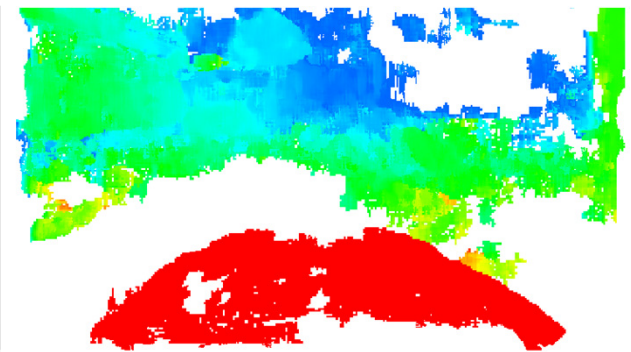


Color image

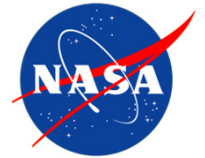


LWIR image

- Candidate vehicle blob
- Ground truth vehicle
- True positive classification

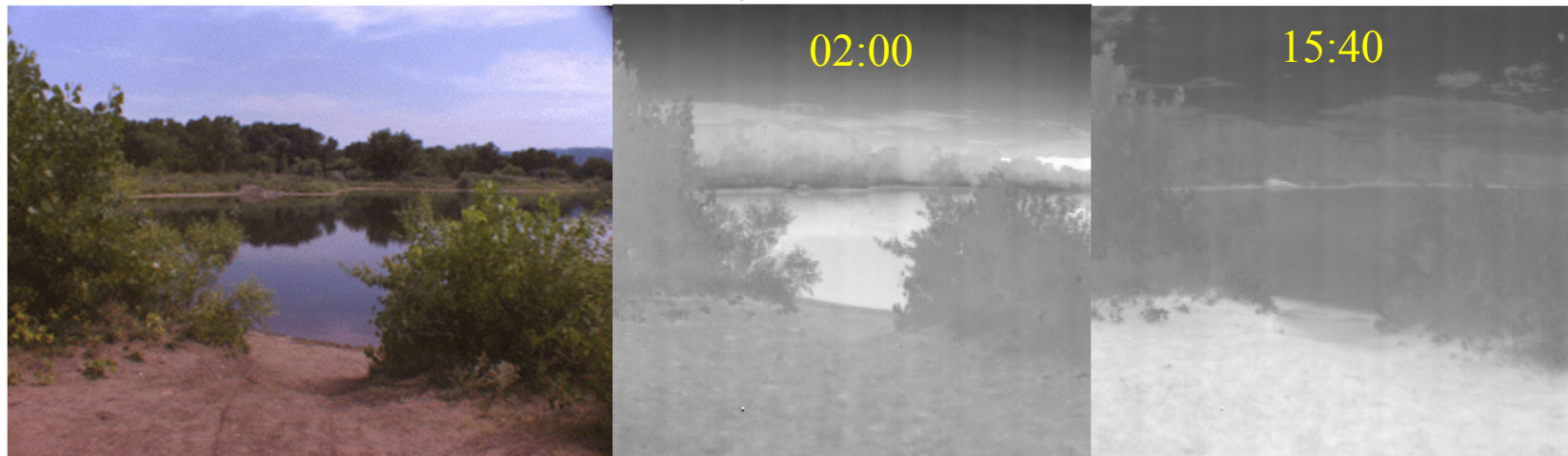
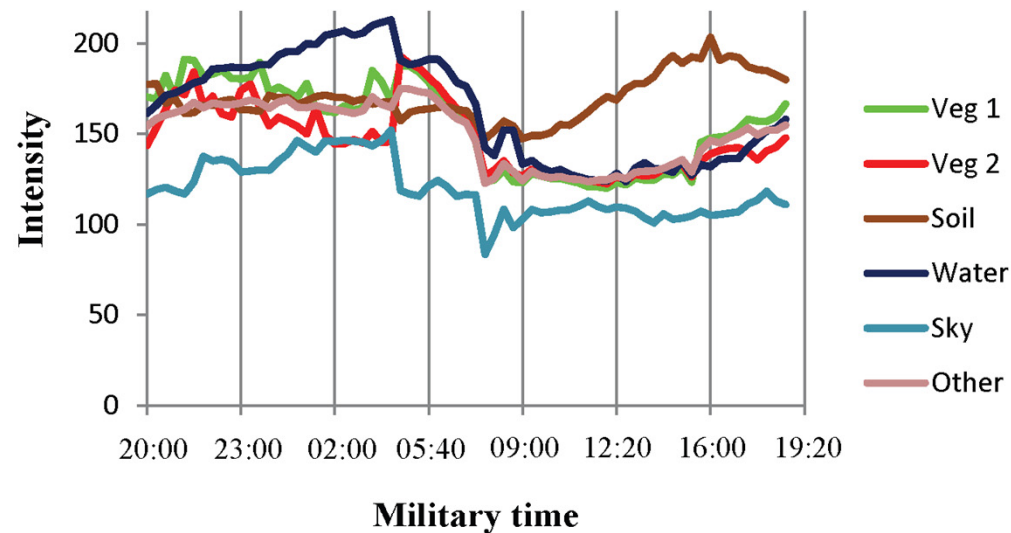


LWIR Stereo range image



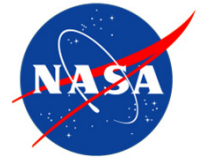
Water Detection

- A 24 hour MWIR data collection was performed on a water body
- The water body was warmer than other terrain types from 2-5am

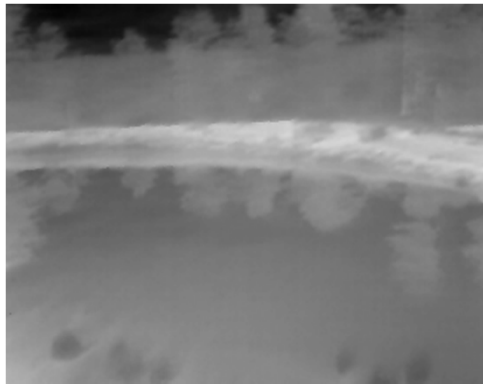




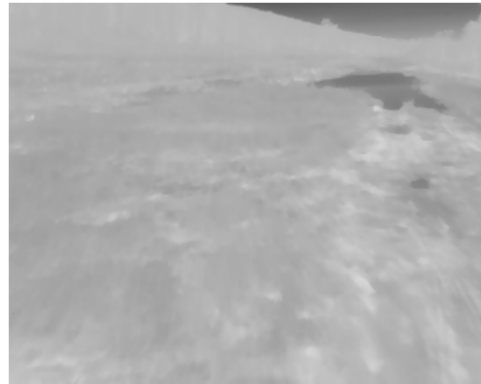
Water Detection



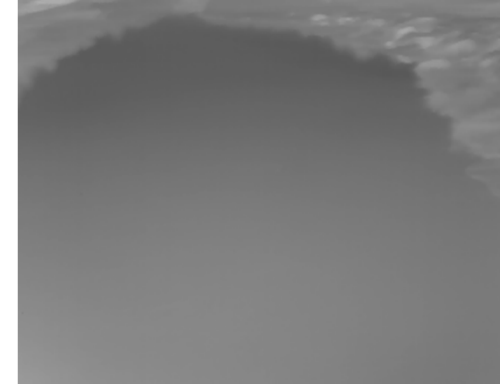
- Cues for water from TIR intensity images and stereo



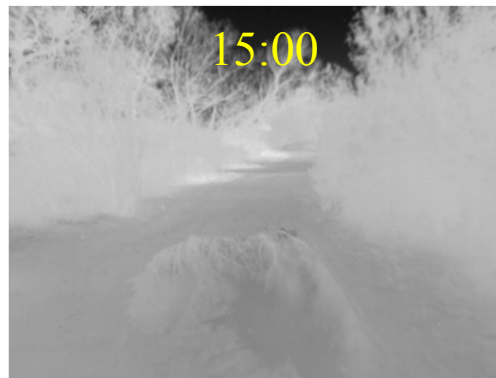
Water in cluttered area:
Reflections of objects in the background



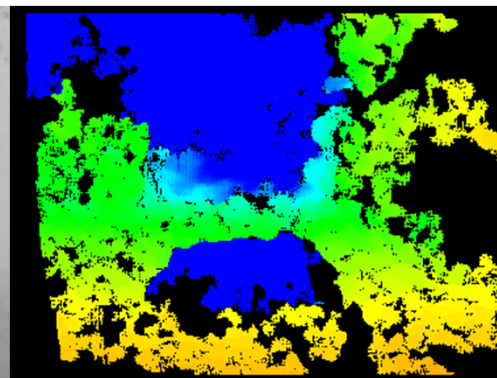
Far water in open area:
Intensity similar to the sky



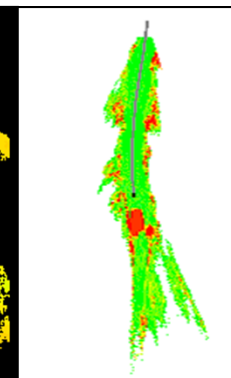
Close water in open area:
Intensity increases with increasing incidence



Left rectified image



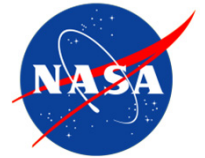
Stereo range image



100m map

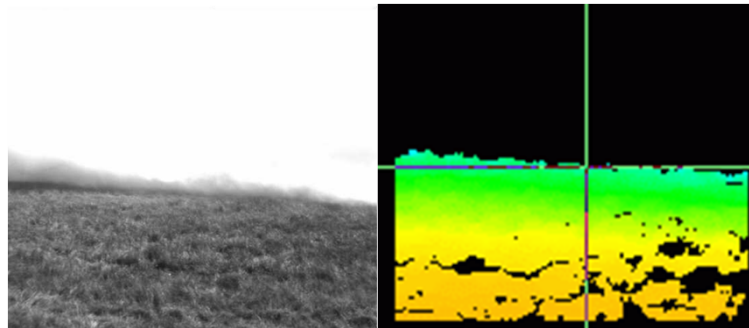


Perception thru Obscurants



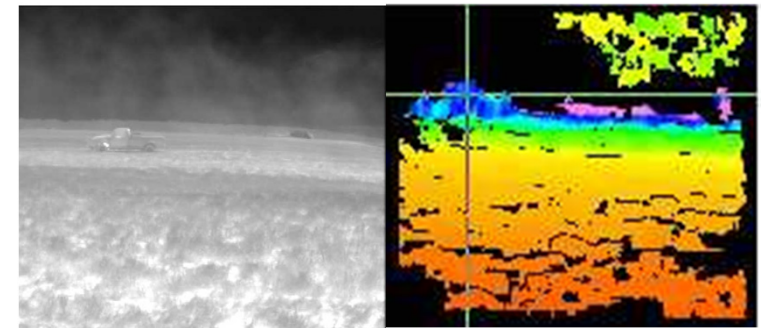
- Detect emitted energy through fog, dust, rain, snow, and some types of smoke

Fog oil
smoke



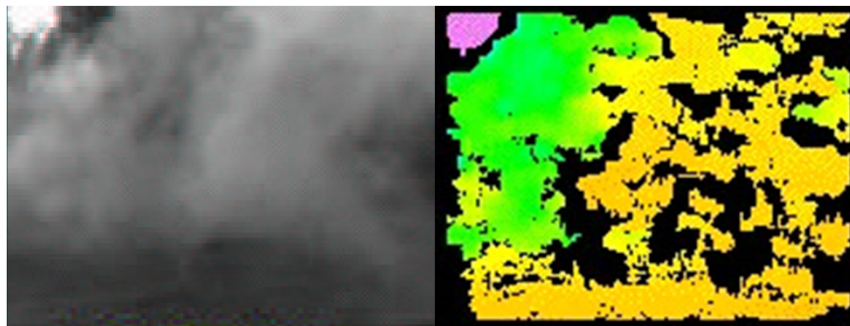
Visible image

Visible stereo range



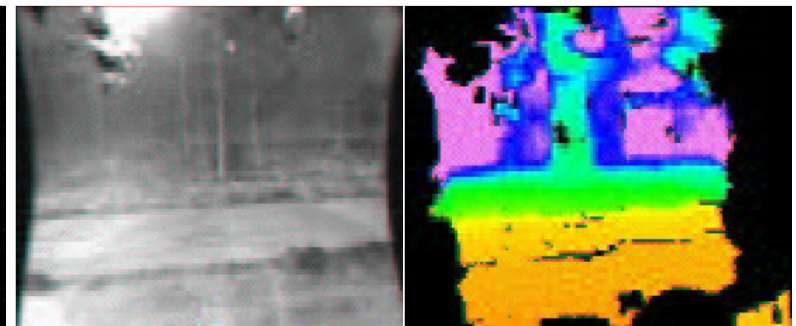
MWIR image with MWIR stereo range
truck at 40m

HC
smoke



Visible image

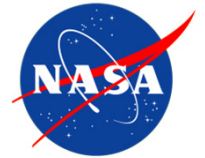
Visible stereo range



MWIR image of
forest



Perception thru Obscurants



Color camera

Photon 640 LWIR camera

Fog

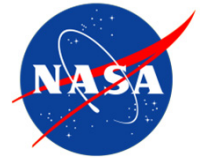


Smoke
from a
controlled
burn

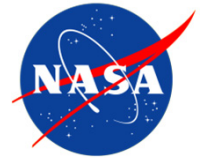




Summary



- TIR cameras can be used for day/night UGV autonomous navigation when stealth is required
- The quality of uncooled TIR cameras has significantly improved over the last decade, making them a viable option at low speed
- Limiting factors for stereo ranging with uncooled LWIR cameras are image blur and low texture scenes
- TIR perception capabilities JPL has explored includes:
 - single and dual band TIR terrain classification
 - obstacle detection (pedestrian, vehicle, tree trunks, ditches, and water)
 - perception thru obscurants



Questions?